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Framework to support impact analyses of renewal strategies of forestlands affected by mountain pine beetle

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Abstract

We developed a decision-support framework that integrates scenario analysis and multi-criteria decision analysis and used it to analyze forest renewal in the study area within the Quesnel Timber Supply Area. Two consensus-based scenarios were constructed to represent the target future conditions: *strong forest sector* and *forest resilience/economic diversification*. Renewal strategies were constructed using multi-criteria decision analysis and sets of criteria specific to each scenario.

Impacts of the renewal strategies are measured in terms of several timber and non-timber indicators. The key economic and timber-related impacts are linked to merchantable volume. Ecological impacts are assessed by analyzing wildlife communities associated with the broad habitat categories.

None of the strategies generated for the scenarios was acceptable in terms of all criteria and outcomes. Further revisions of the scenarios and criteria, with the involvement of local stakeholders, is therefore recommended for decision-making.

The integrated framework developed for this study is general and allows for other community and forest management concerns to be incorporated. The framework demonstrates how the stakeholders' goals regarding their community's future are formulated and how the conflicts between multiple criteria may be addressed.

Keywords: compromise programming, mountain pine beetle, multi-criteria decision analysis, Quesnel TSA, stakeholders, scenario analysis.

Résumé

Nous avons élaboré un cadre d'aide à la prise de décision qui intègre une analyse de scénarios et une analyse décisionnelle multicritères. Le cadre a subséquemment été mis en œuvre pour analyser la régénération forestière dans la zone étudiée de la Zone d'approvisionnement forestier Quesnel. Par le truchement d'un processus d'élaboration de scénarios, deux scénarios axés sur le consensus ont été réalisés pour représenter les conditions cibles futures : « Secteur forestier dynamique », « Résilience de la forêt/Diversification de l'économie ». Avec un ensemble de critères formulés pour chaque scénario, plusieurs stratégies de régénération sont élaborées en utilisant une analyse décisionnelle multicritères.

Les incidences des stratégies de régénération sont mesurées en fonction de plusieurs indicateurs de produits forestiers ligneux et non ligneux. Les principales incidences connexes à l'économie et aux produits du bois sont liées au volume marchand. Les incidences écologiques sont évaluées en analysant les communautés fauniques typiquement associées aux grandes catégories d'habitats.

Aucune des stratégies conçues pour les différents scénarios n'était acceptable au regard de tous les critères et des résultats additionnels étudiés. Dans le contexte de la prise de décision, cette conclusion donne lieu à des révisions supplémentaires des scénarios et des critères avec la participation des parties intéressées locales.

Le cadre conceptuel intégré élaboré pour la présente étude est d'application générale et prévoit que d'autres groupes de gestion des communautés et des ressources forestières ainsi que d'autres préoccupations y seront incorporés. Ce cadre conceptuel démontre de quelle façon les objectifs des parties intéressées concernant l'avenir souhaité de la communauté sont formulés et comment les incompatibilités entre les multiples critères peuvent être résolues.

Mots clés : programmation de compromis, dendroctone du pin ponderosa, analyse décisionnelle multicritères, zone d'approvisionnement en bois de Quesnel, parties intéressées, analyse de scénarios.

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1 Introduction

The current mountain pine beetle (MPB) infestation in British Columbia is the largest forest insect epidemic in Canada's history. This infestation has significant socio-economic consequences and will challenge forestry and community development practices. Renewing infested forestlands has attracted attention from forest managers interested in mitigating future timber supply gaps, from environmentalists concerned about ecological values, and from forest-dependent communities worried about employment prospects and community stability. The renewal of forestlands is referred to in the report as "promoting the recovery of beetle-damaged forests." Several government renewal programs have focused on addressing mid- and long-term timber supply gaps and challenges of the forestry industry (BC MoF 2005). Impacts of renewal programs are expected to be especially significant for communities that depend heavily on forestry-related jobs and revenues (Wagner et al. 2006). The community views on renewal strategies are not necessarily in line with the views of the government and forest industry.

There are no simple solutions to renewing forests affected by the beetle. This problem has complex and conflicting social, economic, and ecological objectives—namely, to provide a stable timber supply over the short and long term and to maintain employment and ecological values. Many stakeholders must be involved in the decision process, including policy makers, forest managers, community representatives, First Nations, environmental groups, and the public. Uncertainty regarding climate change and its impact on forest ecosystems, and the uncertainty regarding economic development and future forest-product markets, also add to the problem's complexity.

Sustainable forest management requires stakeholders to contribute to decisions on forest management strategies. (This report distinguishes between renewal treatments and strategies: a *treatment* is a stand-level activity, and a *strategy* is a landscape-level combination of treatments designed to meet specific objectives.) Science on its own could hardly promote solutions reflecting stakeholders' diversity of needs, priorities, and preferences, but effective participation in the planning process helps them incorporate local priorities into the forest plans.

This project develops a framework for impact analyses of alternative strategies for renewing forestlands affected by the mountain pine beetle. Rather than starting from a set of pre-defined renewal strategies, we developed our decision framework around stakeholders' goals as a tool to support decision-making processes regarding renewal of affected forests and related development issues. It helps answer several questions of interest to stakeholders:

- How are the goals of forest renewal for a specific community determined?
- How are possible socio-economic and ecological impacts of the alternative strategies measured?
- How are renewal strategies developed to meet the defined goals?
- What are the tradeoffs arising from the implementation of specific strategies?
- How can the renewal strategies be evaluated?
- How can several renewal alternatives be prioritized?

2 Methods

We developed a decision-support framework that integrates two methodological approaches: scenario analysis and compromise programming, and used it to analyze forest renewal in the study area within the Quesnel Timber Supply Area (TSA).

2.1 Scenario analysis

Scenario analysis was developed primarily in response to drawbacks of probability based forecasting techniques in long-term strategic planning. Using scenarios as tools that present desirable futures in a rigorous and policy-relevant way is an increasingly popular choice in addressing problems involving multiple objectives, several stakeholders and uncertainty (Berkhout et al. 2003). In this project we use normative scenarios which are built on different visions of the future.

Normative scenarios also aim to explore pathways or strategies that may lead to desirable visions of the future. The scenarios were constructed independently of the strategies. The target situation can be designed as a consensus-based scenario through a scenario-development process. While scenario analysis focuses on uncertainties, it cannot develop the strategies or evaluate their performance (Durbach and Stewart 2003; Montibeller et al. 2006). In practice, scenario analysis works best when it is integrated with other methods that allow for quantification of strategies (Holmberg and Robert 2000; Kosow and Gassner 2008). In this project, we employed the scenario analysis to present preferences of local stakeholders about community futures; the scenarios were further integrated with compromise programming, a multi-criteria decision analysis technique.

2.2 Multi-criteria decision analysis and compromise programming

Multi-criteria decision analysis (MCDA) is a methodological approach designed for developing and evaluating alternative strategies while accounting for multiple, and often conflicting, objectives (Belton and Stewart 2001). MCDA techniques provide a set of analytical tools that decision-makers can use to explore the tradeoffs in the context of the problem and articulate their preferences.

MCDA can be narrowly defined as an approach to help decision-makers identify a strategy that maximizes their satisfaction with several criteria. One way to solve a MCDA problem is to construct an aggregate criterion to be optimized; many such schemes have been suggested. One such scheme is to seek alternatives that minimize the distance between the current criteria values and the target values (or desirable futures). This approach forms the basis for compromise programming and other successfully implemented MCDA techniques (Jones and Tamiz 2003).

Compromise programming is described further in a context of the forest renewal problem with multiple criteria.

Denote by $x \in FS$ a strategy from a set of feasible renewable strategies FS and by $q \in Q$ a criterion index from the criteria indices set Q. Each strategy x can be evaluated in terms of several criteria; such an evaluation is represented by the scores $f_q(x)$, $q \in Q$. Assume that a multi-criteria decision model is formulated as:

$$\max_{x \in FS} \{f_q(x) : q \in Q\}. \tag{1}$$

The meaning of (1) is to find strategies that optimize simultaneously all criteria. The use of maximization in (1) does not reduce the application of the approach. Minimization is directly converted into maximization by using:

$$\min f(x) = \max[-f(x)].$$

In real-life problems, criteria usually conflict, and rarely will a feasible strategy achieve the best value for each criterion. Nevertheless, an *ideal* point that consists of the best criteria values would be a natural planning target. The best criteria values over the set of feasible strategies can be determined by solving a series of (single-criterion) optimization problems:

$$f_q^* = \max_{x \in FS} f_q(x), \ q \in Q \tag{2}$$

whereas the worst criteria values are determined by solving:

$$f_{g^*} = \min_{x \in FS} f_q(x), \ q \in Q. \tag{3}$$

The best criteria values

$$f_q^*, q \in Q$$

are incorporated into an *ideal* vector f^* and used as a reference point. Another point of interest is a *nadir* vector f_* that includes the worst criteria values

$$f_{q^*}, \ q \in Q.$$

Solving optimization problems (2) and (3) could be a challenging task, but it is possible instead to use the upper and lower estimated values for each criterion as the components of the ideal and nadir point.

Both *ideal* and *nadir* values are used to construct an aggregate criterion in terms of the normalized distance from the desired criteria values. Here, a family of L_π metrics that evaluate distances between points in the criteria space is denoted by

$$L_\pi(w,x) = \{\sum_{q \in Q} w_q^\pi [d_q(x,y,z)]^\pi\}^{1/\pi}, \ \pi \geq 1.$$

Here

$$d_q(x) = \frac{f_q^* - f_q(x)}{f_q^* - f_{q^*}}, \ q \in Q$$

is the distance of the current criterion value from its *best* value, normalized by the range of values

$$f_q^* - f_{q^*}.$$

Weights $w_q \in (0,1)$, $q \in Q$ reflect the relative importance of the criteria and π is a distance parameter, $1 \leq \pi \leq \infty$. The solution to the program

$$\min_{x \in FS} L_\pi(w,x)$$

is the compromise solution to the MCDA model (1) with respect to π and w. The choice of π indicates a particular form of conflict management between the competing criteria. For π=1, the problem becomes

$$\min_{x \in FS} L_1(w,x) = \sum_{q \in Q} w_q d_q(x) \tag{4}$$

and searches for a strategy that minimizes the weighted sum of $d_q(x)$. We refer to this problem as the compromise *sum* and the associated strategy will be called the SUM strategy. The program (4) has a form of the weighted sum aggregate criterion.

2.3 Integrated scenario analysis and compromise programming framework

Both the scenario analysis and MCDA are well-established decision support tools, and integrating them may strengthen each methodology and reduce their drawbacks.

From the community perspective, forest renewal could be seen as a combination of collective actions and capital to produce desired outcomes such as tree species composition, economic net returns, employment opportunities, timber supply and biodiversity preservation. Specific economic, social and ecological indicators allow identifying actions and capacities to achieve the desired goals (Reed et al. 2008).

In finding flexible strategies to move to desirable future conditions, forming guiding principles is more important than determining precise steps. Compromise programming allows exploring tradeoffs along the pathways toward desired conditions. For each scenario of a desired community future and each criterion, (2) was solved to determine the best criteria values. Optimal solutions of (2) were used to generate alternative single-criteria renewal strategies. After determining the distances of the criteria values from their *ideal* values, (4) was solved for a selected set of weights that reflected the relative importance of criteria. The solution to (4) was a compromise SUM strategy.

2.4 Tradeoff analysis

Impacts of the renewal strategies were evaluated using timber and non-timber indicators. The key economic and timber-related impacts were linked to merchantable volume. Ecological impacts were assessed by analyzing wildlife communities associated with the broad habitat categories.

Strategic forest planning models were formulated to examine how, after a mountain pine beetle epidemic, local forests can be renewed to achieve the desired economic and timber supply benefits. The models took into account the effects that current decisions have on the future forest.

Economic, timber supply, and ecological impacts of renewal strategies were assessed using various scenarios of the desired future forest. Economic impacts were assessed using the cumulative discounted net return and harvest volume distribution by grade and tree species. Timber supply impacts were assessed using both cumulative volume and harvest volume over time. The economic diversification and ecological impacts of renewal strategies were assessed using tree species composition. Additional insights into potential tradeoffs between different criteria were provided by analyzing annual harvest volumes over time, the distribution of harvest

volume by grades/species, and the distribution of renewal treatments applied after (salvage) harvest.

Three criteria were used to assess general effects on wildlife: forest age class distribution, tree species composition, and annual harvest area. The forest age class distribution provided an index of wildlife values because many faunal species inhabit only specific seral stages. Although some wildlife species are generalists in their habitat requirements and occur ubiquitously in many habitat types, other wildlife species require the structural and stand attributes characteristic of specific stand types. The seral-stage requirements of wildlife in British Columbia are generally well documented and therefore can be used to make reasonable assessments of habitat value.

Tree species differ in habitat values according to their structural and stand attributes. Tree species with high wildlife values are typically large; provide niche stratification both vertically and horizontally; have deeply fissured bark which provides roosting and foraging sites for wildlife; have decay patterns that favour the creation of well-protected cavities; and occur in complex, close-canopied stands. To the extent that the lodgepole pine is relatively small, short, thin-barked, lacking in cavities, and typically occurs in open, even-aged stands with low shrub cover and structural complexity, it is considered lower in habitat value than Douglas-fir and white spruce, among others. Deciduous trees, though not always large, offer important wildlife habitat because they are relatively short-lived and produce the right kind of decay conditions earlier in the rotation. Furthermore, their leaf litter and associated invertebrate, fungal and lichen communities encourage the proliferation of small mammals and birds.

The harvested area provides an index of wildlife impacts because extensive harvesting will lead to the isolation and fragmentation of critical wildlife habitats. In general, small and isolated forest fragments will lose species faster and be more susceptible to local extinctions than larger or less isolated forest patches. Forest fragmentation results in movement barriers to migrating animals and prohibits interbreeding of sub-populations. For these reasons, isolated forest fragments typically do not support the same biodiversity as a single contiguous forest with an equivalent area.

Assessing the effects of management strategies on wildlife values required identifying the wildlife species potentially occurring in the Model Land Base (MLB), since each species responds differently to management actions. Wildlife species in the Quesnel area and their habitat requirements were identified based on distributional range maps for wildlife in the province and from known natural histories (McTaggart-Cowan and Guiguet 1956; Green and Campbell 1984; Gregory and Campbell 1984; Ehrlich et al. 1988; Campbell et al. 1990a, b, 1997, 2001; Peterson 1990; Roberts and Gebauer 1992; Nagorsen and Brigham 1993; Nagorsen 1996; Shackleton 1999; Eder and Pattie 2001; Bunnell et al. 2004; Chan-McLeod and Bunnell 2004; Nagorsen 2005).

A major limitation of the above methodology is that the indices used to assess wildlife habitat values were aspatial and did not consider distributional or site effects which may profoundly affect conservation values. Furthermore, the analyses focused on proportional differences between renewal strategies, but there may be instances when differences in absolute values may be more meaningfully interpreted with respect to wildlife habitat values. Finally, large inter-annual fluctuations in the measures used to assess wildlife values often meant that the ranking of

the renewal strategies changed on an annual basis; for this reason, comparison of renewal strategies was conducted using both the end of planning horizon results as well as cumulative differences over the horizon (i.e., the horizon mean values).

3 Implementation of the Integrated Scenario Analysis–Compromise Programming Framework

3.1 Study area

The city of Quesnel, located in the central interior of British Columbia, is the commercial centre of the North Cariboo (QCEDC 2005). The city is well served by rail, road, and air connections to other major centres in British Columbia. The Quesnel Timber Supply Area (TSA)—see Figure 1—covers approximately 2 million ha and includes the communities of Quesnel, Red Bluff, Barlow Creek, Dragon Lake and Bouchie Lake.

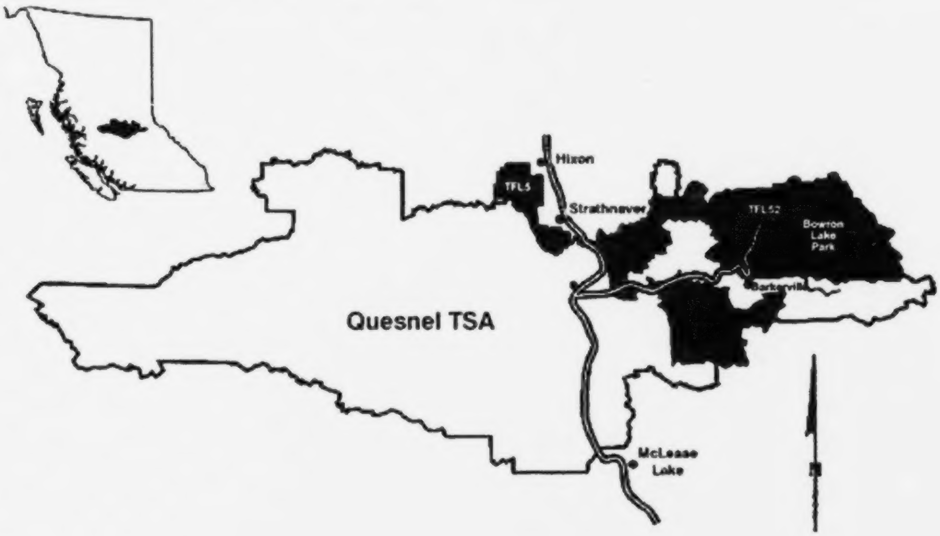

Figure 1. Map of the Quesnel TSA (BC MFR 2007b).

In 2006, the population of the Quesnel area was 22,449 people within a radius of 50 km from the city centre (Statistics Canada 2009). Four First Nations bands—Alexandria, Kluskus, Nazko and Lhtako Dene (Red Bluff)—live in the area. The forest industry dominates the region, both in terms of employment and community income: all together, more than 3,000 people work in the two pulp mills, five large sawmills, plywood plant, medium-density fibreboard plant, and smaller value-added manufacturing operations in the area. The forest industry contributes at least 30% to the direct and indirect income of the Quesnel community.

3.2 Scenario development for the Quesnel study area

The community's dependence on the forest industry means decision-makers should consider many perspectives of post-beetle renewal strategies. Local stakeholders are critical to this process, as they ensure a coordinated approach to planning, communication, and implementation.

Previous studies have shown that the beetle infestation has imposed a pressure on community capacities to respond to stress and to make decisions about future development (Kusel 2001; MacKendrick and Parkins 2005; QCEDC 2005). The renewal programs developed and implemented in the near future will have the capacity to shape the community's social and economic conditions as well as those of the forest ecosystems over the long term.

The Quesnel community has recently experienced a boom in wood processing mainly due to a large amount of infested wood that had to be processed within the shelf-life timeframe. Several analyses have warned consistently about an imminent mid-term gap of timber supply (BCMF 2005). The current grim outlook and the future prospects for the Quesnel community are the result of several factors, including a quantity of mature pine forests, changes in trade relations and market prices for wood products, impacts of changing weather and climatic patterns, and the community's dependency on the forest sector.

To obtain information regarding desired community futures, two workshop sessions were organized: one session involved representatives of the forest industry and provincial government, while another included members of the public, local municipality, and non-governmental environmental groups. The two sessions were held in Quesnel on March 25–26, 2008 and involved 11 participants. During the workshop, the participants discussed desired community futures related to forest renewal using a pre-determined list of economic, social, and ecological indicators. The initial list of indicators served as a start-up and guide for the discussion. The list was further changed to capture issues raised during the discussion. The scenario development process is presented in Figure 2.

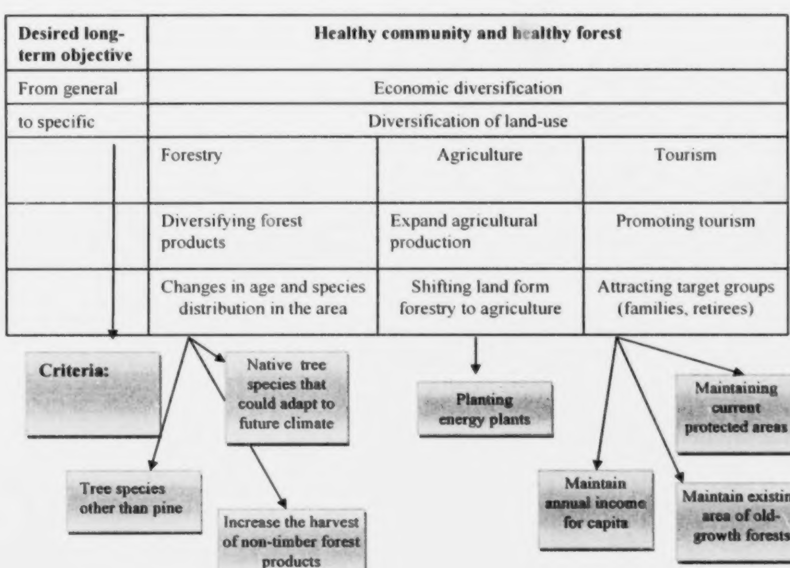

Figure 2. Quesnel scenario development process.

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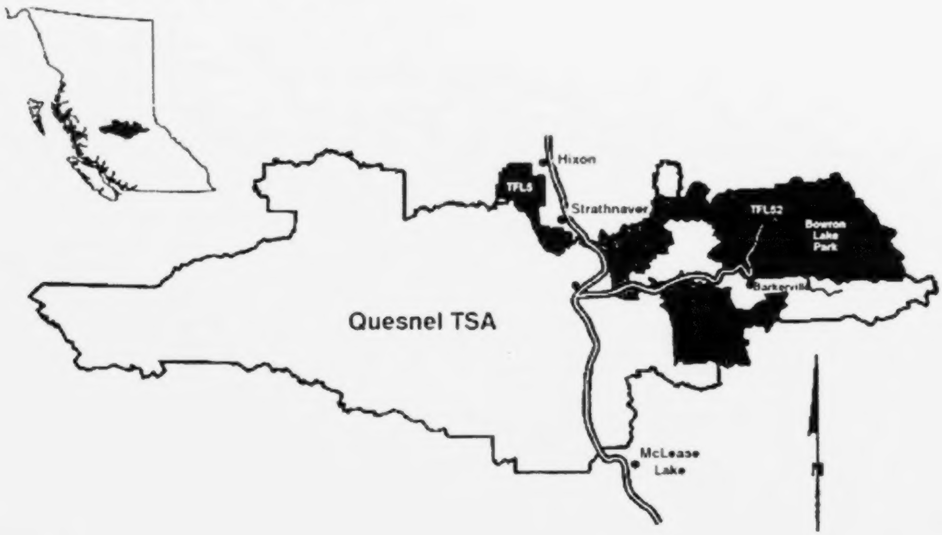

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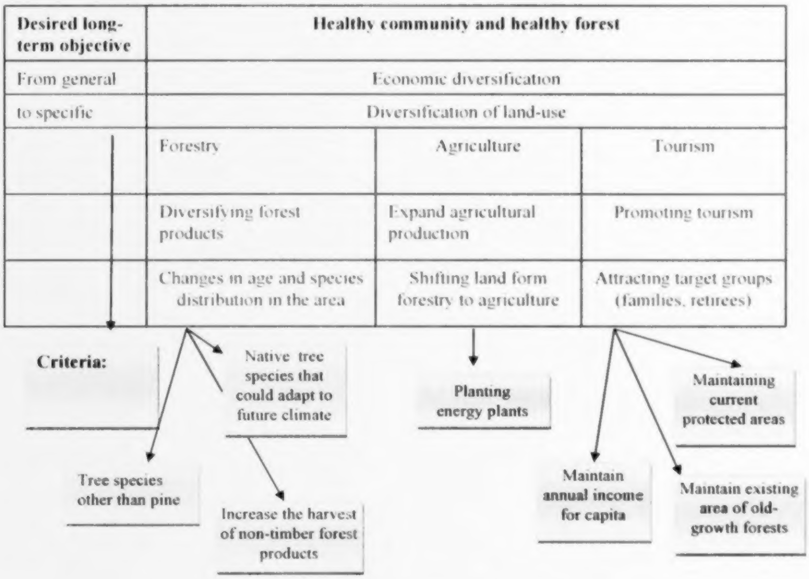

Figure 2. Quesnel scenario development process.

The planning time horizon was among the first tasks tackled at the workshop. The key forestry issues and related aspects of the community's future have changed in the last five years. Comparing early predictions about the mid-term timber supply gap around 2030 (Eng et al. 2005) with the latest ones that put the beetle-induced timber shortage much earlier, most likely by 2020, provoked a sense of urgency among workshop participants. This atmosphere of urgency has shaped the views of participants on what should be considered short-, medium- and long-term time horizons. They agreed that the three time horizons should respectively span 1–10 years, 11–30 years, and more than 30 years. Further, the first two planning horizons were amalgamated into one (1–30 years) and called *mid term* in this report. Thus the mid term and long term were used in the evaluation of participants' preferences regarding various indicators.

At the end of each workshop session, participants were asked to evaluate the indicators over the mid and long term by using a scale from 0 to 100. A zero score means the indicator is irrelevant to guiding the forest renewal strategy toward a desired future, and a score of 100 expresses the highest importance of that indicator. The average score for each indicator over the mid and long term are presented in Table A1 (see *Appendix I*).

3.3 Stakeholders' preferences for different scenarios

Because of the participants' different profiles in the two workshops, it came as a surprise that in both sessions the highest priority was assigned to the scenario *exploring opportunities and impacts of economic diversification*, which focuses on diversifying the regional economic base. This scenario aims to reduce community reliance on the forest sector and to develop other sectors including tourism, agriculture, mining, and retirement services. The scenario has also been seen as a way to maintain regional employment levels and income per capita. Considering sectors other than forestry is beyond the scope of this project; we therefore formulated the related scenario *forest resilience/economic diversification* that focuses on the structural diversity of forests and forest sector diversification that may be achieved by changing the tree species composition.

After analyzing the workshop outcomes, two key scenarios of desired futures for Quesnel were identified: a strong forest sector and forest resilience/economic diversification. Characteristics of the two scenarios are presented in Table 1.

Table 1. Scenarios of desired futures for Quesnel.

Scenario/Goals	Indicators
Scenario I: Strong forest sector	
Achieve high economic returns from forest sector	Net present value
Maintain high and stable timber supply	Cumulative harvest volume; even harvest flow
Species composition: planting regional coniferous species	
Scenario II: Forest resilience/economic diversification	
Diversify tree species	Meet target tree species composition
Maintain high and stable timber supply	Cumulative harvest volume; Even harvest flow
Species composition: planting regional coniferous species, western larch[a] and aspen[b]	

[a] Tree species suitable for planting in the Quesnel area under the projected climate change (Hamann and Wang 2005).

[b] Fast growing tree species suitable for multiple uses.

3.4 Description of the land base

The Quesnel Forest District is made up of the Quesnel TSA, Tree Farm Licenses 5 and 52, and numerous woodlot license areas (BC MFR 2007a). The TSA covers approximately 2 million ha, of which 81% is considered productive. The productive forest is roughly 1.31 million ha, with 69% of this area classified as timber harvesting land base (THLB). The model-planning horizon is 200 years, starting in 2010. Currently immature stands (recently harvested or natural) are assumed to have assigned renewal strategies. The area considered in this model, referred to as the MLB, includes THLB stands older than 40 years. The MLB is 621 953 ha or about 63.7% of the THLB. Land base classification details are presented in Table 2.

Table 2. Quesnel TSA land base classification.

Land base classification	Area (ha)	Percentage of THLB (%)
Total land base area	2 077 267	100.0
Crown forested land base	1 310 324	63.1
Non-contributing land base	330 096	15.9
Timber harvesting land base (THLB)	975 667	47.0
Model land base (MLB)	621 952	29.9

The MLB is divided into strata according to tree species, site index and age classes, biogeoclimatic (BEC) zones, and severity of beetle attack. The forest resources include four predominant species: interior Douglas-fir, spruce (except black spruce), lodgepole pine, and deciduous species (mainly aspen) growing on the three productivity site index classes of poor, medium, and good.

Table 3 shows the initial tree species distribution. The area of pine-leading stands totals 486 381 ha (about 79.2% of THLB), which is a conservative estimate that does not account for pine as a secondary-stand species.

Table 3. Distribution among tree species within the MLB.

Species group	MLB area (ha)	Percentage of the MLB (%)
Fir	30 436	4.9
Spruce	80 297	12.9
Regular pine stands	383 284	61.6
Pine leading problem forest type (PFT)	103 098	16.6
Deciduous	24 837	4.0
Total	621 952	

The initial distributions among tree species and site index classes, among tree species and age classes, and among tree species and BEC zones within the Quesnel MLB are summarized in Tables A2, A3, and A4, respectively, of *Appendix II*.

3.4.1 Mountain pine beetle attack

The beetle attack data for the Quesnel TSA are available as a percentage of the area of susceptible stands. Since the Quesnel attack data are considered incomplete, our models use the assumption that severe beetle attacks (81%–100% stand loss) have occurred by 2007 in all pine-leading stands older than 30 years (BC MFR 2007c; Eng et al. 2005). For the remaining stands, we use data of stand attacks provided by FESL (2008). Stands are classified into three categories: non-attacked (NA), attacked (A), and managed (M). All NA and A stands undergo a transition to a managed state upon harvest. All NA and A stands can also remain as standing inventory depending on the scenario and the model criteria.

Each stratum is assigned to existing and future yield table projections. For the existing stands, yield data from FESL (2008) are used and future yield projections are generated by TIPSY 4.1 (BC MFR 2007e).

All current stand yield data are derived from individual stem information which allows the breakdown of volume by species and tree diameter classes (< 20 cm DBH, 20–30 cm DBH, and >30 cm DBH)—see Moss 2007. Four grades of logs (1, 2, 4 and 6) are considered based on log size. Non-attacked stands use a grade distribution by log size presented in Table 4.

Table 4. Grade distribution by log size before beetle attack.

	Percentage (%) of merchantable volume								
Log size	<20 cm			20–30 cm			>30 cm		
Grade	2	4	6	1	2	4	1	2	4
Regular pine stands	89	8	3	6	83	11	56	38	6
PFT pine-leading stands	95	2	3	6	83	11	56	38	6

Source: FESL (2008).

A significant uncertainty exists about how long beetle-killed wood will be usable (*shelf-life*). Salvage treatment uses the same volume yield curves as non-attacked stands, but with different merchantability rates for the percentage of various products recovered. We do not model the beetle attack because of the models' focus on strategic planning and the choice of a 10-year planning period. Our models assume that beetle-killed wood can be harvested for 20 years before becoming completely un-merchantable.

Attacked stands have the same total merchantable volume as before the attack, but use the merchantability rates presented in Table 5. Attacked-stand tables also contain the amount of waste, called the un-recovered (UR) grade.

Table 5. Grade distribution by log size and shelf-life after beetle attack for regular pine and pine-leading Problem Forest Type (PFT) stands.

	Percentage (%) of merchantable volume											
Log size	*<20 cm*				*20–30 cm*				*>30 cm*			
Grade	2	4	6	UR[c]	1	2	4	UR[c]	1	2	4	UR[c]
Years after attack	*Regular pine stands*											
5[a]	37	31	3	29	1	40	36	23	2	29	24	45
15[b]	10	43	2	45	0	5	35	60	0	0	10	90
Years after attack	*PFT pine lead stands*											
5[a]	62	20	3	15	1	40	36	23	2	29	24	45
15[b]	10	53	2	35	0	5	35	60	0	0	10	90

[a]mid-point of period 1 (1–10 years).
[b]mid-point of period 2 (11–20 years).
[c] un-recoverable (UR).
Source: FESL (2008)

3.5 Management assumptions used in modeling the case study

Stands are assumed to be harvested when their volume reaches at least 140 m^3/ha. Various treatments have been suggested to regenerate beetle-attacked stands (Mitchell 2005). Management assumptions used in developing models for the Quesnel TSA are based on several documents: a Mountain Pine Beetle Program project and MSc thesis developed for Canfor's TFL 48 in northeastern British Columbia (Seely et al. 2008; Moreira-Muñoz 2008), and two consulting reports developed for the Quesnel TSA (Buell et al. 2006; FESL 2008).

Following an approach suggested by Seely et al. (2008) for salvage/regeneration in TFL 48, our models are designed to choose between several salvage/regenerations treatments for each stratum. Treatments are designed to increase productivity (treatment P) or reduce the risk of future beetle outbreaks by planting non-pine species and/or tree species adaptable to future climate change (treatment R). Two other treatments also considered are no salvage harvest and a default treatment. The four alternative salvage/renewal treatments are as follows:

Natural (N): No salvage and natural regeneration that reflects the percent of pine and other mature species at the time of beetle attack.

Default (D): Clearcut approach with planting and natural regeneration that reflects pre-harvest species composition.

Productivity (P): Clearcut, pine planting, and fertilization applied to stands of SI classes medium and high.

Risk (R): Clearcut of attacked pine stands and planting alternative species.

4 Multi-Criteria Modelling Under Different Scenarios

Forest renewal is a complex planning problem that involves multiple conflicting criteria. Rather than optimizing a selected criterion, either economic, social or environmental, while imposing restrictions on remaining goals, the forest renewal problem is formulated as a series of multi-criteria linear programs under two scenarios. Forest attributes are aggregated into management strata $m \in M$. Let M be the set of management strata, T the number of 10-year periods over the 200-year planning horizon, and $TS < T$ the number of periods considered for short to medium planning.

If specific forest characteristics are to be emphasized in the model, M can be partitioned accordingly. We consider tree species composition s∈S, where S is the index set of tree species. Denote by

$$M_s \subseteq M$$

a partition of M by tree species g such that

$$M_i \bigcap M_j = \varnothing,\ M = \bigcup_i M_i,\ i, j \in S.$$

Let $P(m,t)$ be the set of renewal treatments appropriate to stratum m in period t. Renewal treatments include various combinations of salvage harvest and renewal activities. A decision variable

$$x = x_{mpt}$$

represents the area (in ha) of forestland of stratum m managed by treatment p in period t. The feasible set FS for all models consists of the technical constraints on land availability, harvest, renewal, and silviculture activities; the initial and terminal timber inventories; and the non-negativity constraints. In addition to the technical constraints, a constraint on the annual harvest volume is introduced. The constraint is based on the current Annual Allowable Cut for the Quesnel TSA of 5.280 million m^3 established for the THLB. For the MLB area of 621 953 ha (63.7% of the THLB area), the upper bound of the annual harvest volume is set up at 4 million m^3. This is an arbitrary value that may affect the projected outcomes. Because of other uncertain parameters that play a significant role in the model, this analysis should be considered only in the context of the assumptions made and input data provided.

The success of renewal strategies in accomplishing multiple goals under different scenarios of desired community futures is measured using social, economic and environmental criteria. Under Scenario I, two criteria are considered: economic and timber supply. The economic criterion consists of the net discounted returns from forestland across the planning horizon. The timber supply criterion is formulated as the achievement of a high and even supply of timber over the horizon.

Scenario II considers forest diversity and timber supply in exploring forest resilience and economic diversification. The forest diversity can be measured in relation to some desired *target* tree species composition. Probably the best way of establishing the desired target is to rely on expert opinions and/or public expectations for a desired future forest composition. These opinions and expectations might differ significantly. Our criterion of forest diversity is measured relative to specific tree species composition targets established for mid- and long-term horizons. The criteria formulated for the two scenarios are presented in Table 6.

Table 6. Criteria formulated for different scenarios.

Scenario/Goal	Criterion
Scenario I: Strong forest sector	
Achieve high economic returns from forest sector	Max net present value
Maintain high and even supply of timber	Max cumulative harvest volume
	Min and max deviation from even flow
Renewal treatments: natural; default; productivity and risk (planting regional coniferous species)	
Scenario II: Forest resilience/ Economic diversification	
Diversify composition of tree species	Min max deviation from target tree composition
Maintain high and even supply of timber	Max cumulative harvest volume
	Min and max deviation from even flow
Renewal treatments:	
Natural; default; productivity and risk (planting regional coniferous species, western larch[a] and aspen[b])	

[a] Tree species suitable for planting in the Quesnel area under the projected climate change (Hamann and Wang 2005).
[b] Fast growing tree species suitable for multiple uses.

4.1 Scenario I Model

The economic criterion consists of net discounted returns to forest management, while the timber supply criterion addresses concerns related to the adequate supply of fiber for mills and satisfying contractual obligations with the Province and industry. The latter goal is typically accomplished through the even flow of harvest volume over time. We couple even flow with maximization of cumulative harvest volume because this drives fiber supply as high as possible.

To examine how local forests can be renewed after a beetle epidemic to achieve the desired economic and timber-supply benefits, strategic forest planning models are formulated. The dynamic character of the models takes into account the effect that current decisions have on the future state of the forest.

The criteria functions are stated as:

Discounted net revenue: $$N(x) = \sum_{m \in M} \sum_{t=1}^{T} \sum_{p \in P(m,t)} (1+r)^{-t \times 10} \; nv_{mpt} \, x_{mpt}$$

Cumulative timber volume: $$V(x) = \sum_{m \in M} \sum_{t=1}^{T} \sum_{p \in P(m,t)} v_{mpt} \, x_{mpt}$$

Maximum harvest flow deviation: $$FlowD(x) = \max_{t} | Vol_{t+1}(x) - Vol_{t}(x) |$$

Where v_{mpt} denotes the merchantable volume from a hectare of stratum m managed by treatment p in period t, nv_{mpt} is the net revenue per hectare of stratum m managed by treatment p in period t, and r is the discount rate.

Here,

$$nv_{mpt} \; (\$/m^3)$$

is the difference between a discounted revenue and costs that results from applying treatment p to stratum m in period t. The revenue,

$$r_{mpt} \; (\$),$$

depends on the quantity and quality of the volume harvested; the merchantable volume is categorized into different grades which draw different prices. The grade is based on the length and diameter of the log pieces. The revenues are calculated as:

$$r_{mpt}(\$) = a_{s,g}(\$/m^3) \times v_{mpt}(m^3)$$

where $a_{s,g}(\$/m^3)$ is the price per cubic metre of species s and grade g wood. Selling prices by species and grades used in this project are presented in Table 7. The prices are provided by FESL (2008) and adjusted using some of the prices provided for the Interior of British Columbia by the Ministry of Forests and Range (BC MFR 2007d)

Table 7. Selling prices by species and grade.

	Selling prices ($/m³)		
	Grade		
Species	1	2	4
Fir	57.77	57.77	27.61
Spruce	47.23	47.23	31.93
Pine	47.23	47.23	39.58
Deciduous	26.00	26.00	26.00
Western Larch	57.77	57.77	27.61

Sources: FESL (2008); Moreira-Munoz (2008).

The costs consist of silviculture costs slv_{mpt} ($/ha) and harvest costs hc_{mpt} ($\$/m^3$) (Table 8). Both costs are assumed to depend on the BEC zones only.

Table 8. Silviculture and tree-to-truck cost by BEC zone.

	Cost	
BEC zone	*Silviculture* ($/ha)	*Tree-to-truck* ($/m³)
ESSF	1626.32	17.87
ICH	1674.00	17.63
IDF	586.62	18.05
MS	740.00	17.00
SBPS	779.50	16.16
SBS	1037.74	16.16

Source: FESL (2008).

The timing of silviculture treatments is predetermined and costs of silviculture treatments ($/ha) are discounted to the time of the initializing harvest. Harvest costs include both administrative and operational components, which are associated with tree felling and road construction. Because of the non-spatial character of the models, we do not include transportation costs in the analysis.

The model also calculates the amount of waste, the unrecovered UR category, to account for the losses due to beetles. The total volume over all grades (including the waste volume) adds up to the total volume of a non-attacked stand at the same time period.

Here, $N(x)$ and $V(x)$ are the respective cumulative discounted net revenue and cumulative harvest volume over the horizon, whereas

$$Vol_t(x) = \sum_{m \in M} \sum_{p \in P(m,t)} v_{mpt} \, x_{mpt}$$

is the harvest volume in period t. $FlowD(x)$ is the maximum absolute difference between harvest volumes in subsequent periods. In the case of even flow, this difference is zero. In other cases, $FlowDev(x)$ reflects the level of variation in timber supply over time. If stability of timber supply is a management goal, $FlowD(x)$ is to be minimized.

For Scenario I, the multi-criteria model is formulated as:

(ScI-MCM)

(NPV)	Max $N(x)$
(VOL)	Max $V(x)$
(EVEN)	Min FlowD(x)
subject to	$x \in FS$

4.2 Scenario II Model

The first goal under Scenario II is to diversify tree species composition. In this model, the corresponding criterion is defined as the maximum deviations of the current (actual) species composition from the desired composition targets, in both the mid and long term.

The timber-supply goal addresses concerns related to adequate fiber for mills and satisfying contractual obligations with the Province and industry. This goal is handled in the same fashion as in the Scenario I model. The criteria functions are stated as

Maximum deviation from target tree composition: $TreeD(x) = \max_s | C_s(x) - TC_s |, s \in M_s$

Cumulative timber volume: $V(x) = \sum_{m \in M} \sum_{t=1}^{T} \sum_{p \in P(m,t)} v_{mpt} \, x_{mpt}$

Maximum harvest flow deviation: $FlowD(x) = \max_t | Vol_{t+1}(x) - Vol_t(x) |$

Here,

$$TreeD(x) = \max_s | C_s(x) - TC_s |, s \in M_s$$

is the maximum absolute difference between the actual $C_s(x)$ and target TC_s abundance of tree species s. Both the actual $C_s(x)$ and target TC_s abundance of tree species s are expressed in terms of portions (%) of the MLB area. When the target tree species composition is fully achieved, $TreeD(x)$ is zero. In all other cases, $TreeD(x)$ reflects the maximum level of deviation from the target composition. If meeting the target tree composition is the goal of forest renewal, then $TreeD(x)$ is to be minimized.

The meanings of $Vol_t(x)$ and $FlowD(x)$ are the same as for the Scenario I model. For Scenario II, the multi-criteria model is formulated as

(Sc II-MCM)

(DIVERS)	Min TreeD(x)
(VOL)	Max $V(x)$
(EVEN)	Min FlowD(x)
subject to	$x \in FS$

5 Results

A compromise programming model developed by Krcmar et al. (2005) was modified and adjusted to deal with the renewal of forestlands affected by the beetle. For each of the two scenarios, a series of linear models was developed and coded in GAMS (Brooke et al. 2004). All programs were solved using the CPLEX solver on the GAMS platform.

For both Scenarios I and II, multiple single-criterion strategies and one compromise strategy were generated. For all strategies, several types of outcomes were calculated and used to assess the economic, timber supply and ecological impacts of management strategies.

Economic impacts were assessed using the cumulative discounted net return. Another indicator of economic impacts is harvest volume distribution by grade and tree species. Timber supply impacts were assessed in terms of both cumulative volume and harvest volume over time.

Ecological impacts were assessed in terms of the wildlife habitat requirements using the following outcomes: forest age class distribution, tree species composition, and annual harvest area. There are 185 wildlife species occurring in the Quesnel TSA: 130 of these are birds, 48 are mammals, 5 are amphibians, and 2 are reptiles. Some can be further categorized as furbearers or big game, two groups that may have particular economic significance. This analysis does not include wildlife species that do not use forested habitats (e.g., waterfowl species that inhabit only open water in large lakes).

Analyses of habitat requirements for wildlife species potentially occurring in the MLB (Table A6, *Appendix II*) reveal that approximately 46% of these species are *generalists* in their habitat needs. In contrast, 23% occur primarily in early successional forests, 9% inhabit mid-seral stages, and 28% occur primarily in mature forests. Forest edges and open habitats are used by 32% of the species. Shrubs are important to 17% of all species, while deciduous trees are important to 23% of all species.

5.1 Economic and timber supply impacts of the Scenario I strategies

First, each criterion function is optimized individually to generate single-criterion management strategies. The values of all criteria calculated at the optimal strategies are presented in Table 9. For example, the elements of the first column are criteria values when net present value (NPV) alone is optimized (NPV strategy). The ideal values—the best possible values of each criterion—are provided in boldface. The underlined figures correspond to the worst criteria values. Figures in parentheses indicate the extent to which the ideal criteria values are reached by the current strategy.

Table 9. Scenario I single-criterion strategies.

	Single-criterion strategy		
Criteria values	NPV	VOL	EVEN
N(x) (million $)	**1186.194**[a] (100.0%)	1129.318 (95.2%)	<u>796.739</u>[a] (67.2%)
V(x) (million m^3)	<u>280.187</u> (85.4%)	**328.102** (100.0%)	293.735 (89.5%)
FlowD(x)[b] (million m^3)	<u>38.056</u> (0.0%)	37.495 (1.5%)	**0** (100.0%)

[a] Best values are given in bold; worst values are underlined.
[b] Expressed as a deviation from the constant period volume.

From the criteria values calculated for the single-criterion strategies NPV, VOL and EVEN, it is clear that all criteria conflict. The conflict is especially marked between economic and timber supply benefits, but there is also significant conflict in achieving both a cumulative and stable timber supply over the horizon. The strategy of maximizing NPV leads to the worst level of cumulative harvest volume. In order to attain the NPV of $1.2 billion, the cumulative volume drops to 280 million m^3 or 85.4% of its highest value. On the other hand, the even flow of harvest is in a strong conflict with financial benefits. When the EVEN strategy is employed, the financial benefit expressed by NPV drops to about 67% of its highest value.

Since none of the single-criterion strategies is fully acceptable, a new strategy is generated to reduce the conflict between the criteria. This new strategy is constructed by solving compromise program (4) with all criteria equally weighted. The SUM column of Table 10 contains the criteria values calculated at the SUM compromise strategy.

Table 10. Scenario I compromise strategy.

	Compromise strategy
Criteria values	SUM
N(x) (mil. $)	1033.231 (87.1%)
V(x) (mil. m^3)	322.640 (98.3%)
FlowD(x) (mil. m^3)	8.998 (76.4%)

While the relative criteria values achieved by the SUM strategy are quite high for financial and cumulative timber supply goals, there are still significant deviations from even flow between the periods. The SUM compromise strategy is obtained under equal weighting of the criteria. By varying weights associated with different criteria, stakeholders may explore other tradeoffs between the strategies.

Additional insights into potential tradeoffs are provided by analyzing the distribution of harvest volume by grades and species (Table 11).

Table 11. Scenario I harvest volume by grades and species.

		Harvest volume (% of cumulative)							
		Grades				Species			
Strategy	Cum.volume (million m^3)	1	2	4	6	Fir	Spruce	Pine	Deciduous
NPV	280.187	5.3	85.2	8.5	1.2	6.8	20.6	66.1	6.4
VOL	328.102	3.8	82.7	10.8	2.5	6.6	21.6	65.5	6.2
EVEN	293.735	4.4	84.2	9.8	1.6	6.6	26.4	61.1	5.9
SUM	322.640	6.2	82.5	9.9	1.3	6.8	25.2	61.9	6.1

While the NPV and VOL strategies are close in terms of tree species harvest, they differ in quantity of grade 1 and grade 2 harvest. To achieve high financial benefits, the cumulative grade 1 and grade 2 harvest for the NPV strategy is 90.5% of the total harvest, compared to 86.5% for the VOL strategy. The EVEN and SUM strategies result in an increased spruce harvest and decreased pine harvest compared to the NPV and VOL strategies.

Analysis of projected outcomes over time for the single-criterion and compromise strategies may help us better understand the sources of conflict, related tradeoffs, and multiple impacts of these strategies. The outcomes selected for analysis are the annual harvest volume and a distribution of management treatments after harvest. Figure 3 illustrates annual harvest volumes over time for the four strategies.

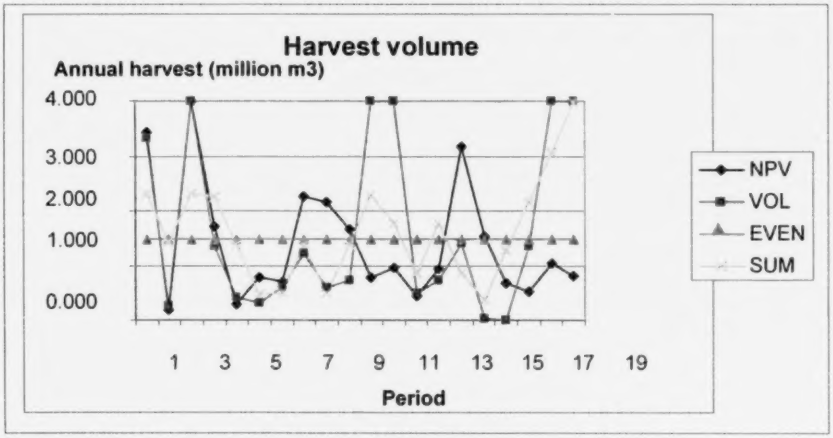

Figure 3. Scenario I annual harvest volumes.

Both the economic NPV and cumulative volume VOL strategies rely on intensive harvesting in the early planning periods. The annual harvest volumes in period 1 reach 3.422 million m^3 and 3.313 million m^3 for the NPV and VOL strategies, respectively. These harvest volumes are achieved on the area of MLB. When these figures are extrapolated proportionally to the THLB area, they are very close to the 2004 Annual Allowable Cut for Quesnel TSA. A direct implication of both the NPV and VOL strategies is a dramatic downfall in timber available for harvest in period 2. Another similar cycle of ups and downs of harvest volume occurs between

periods 3 and 5. The annual harvest volumes for NPV and VOL strategies start diverging at period 6 with more intensive harvest for NPV strategy in periods 8, 9 and 10. The EVEN strategy shows that it is possible to achieve the constant harvest of 1.469 million m^3 over the whole time horizon. We will further explore ecological implications of the EVEN strategy. Despite fluctuations of timber flow, the SUM strategy would be acceptable until about period 5 (i.e., for about 50 years from now). After period 5, the annual harvest volume keeps falling for about 40 years and does not reach the EVEN strategy harvest level until period 8 (i.e., 80 years from now).

The renewal strategies are designed as specific combinations of several renewal treatments. The strategies are compared in terms of the management treatments applied in combination with harvest: default, risk and productivity. For each strategy, Table 12 provides distributions of renewal treatments—default, productivity and risk—in terms of the portions of the total harvest area over the horizon.

Table 12. Scenario I distribution of renewal treatments.

Strategy	Total harvest area (mil. ha)	Renewal treatment (% of harvest area) Default	Risk	Productivity
NPV	1.451	97.6	0.1	2.3
VOL	1.333	98.6	1.4	0.0
EVEN	1.329	94.7	5.1	0.2
SUM	1.296	97.9	2.1	0.0

The NPV strategy that maximizes discounted net economic benefits is characterized by a significant application of default treatment, a modest use of productivity treatment, and an insignificant application of risk treatment (Table 12). Managing for high harvest volume (VOL strategy) leads to greater use of both default and risk treatments compared to the NPV strategy, but no application of productivity treatments. The EVEN strategy that achieves an even harvest flow over the horizon is characterized by a dominance of a default treatment and an increased application of risk treatment to compensate for the lack of pine resources.

In connection with the results in Table 12 a distribution of species planted under the risk treatment reveals that the only difference among strategies is found in the distribution of spruce planting under risk treatment (Figure 4).

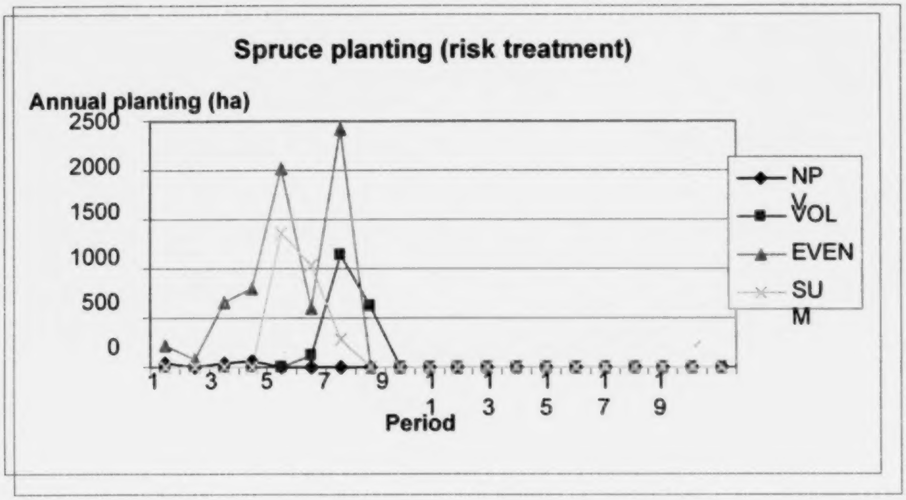

Figure 4. Scenario I risk treatment (spruce planting).

Spruce planting on the beetle-attacked pine stands, an activity within the risk treatment, occurs mainly between periods 3 and 8. Its purpose is mainly to help compensate for reduced harvest volume in the later periods, especially for the EVEN strategy.

A renewal strategy that aims to reconcile conflicting criteria is a combination of the previous extreme strategies. To achieve the minimum average deviation from the best criteria values, the SUM renewal strategy applies default treatment to a much smaller portion of the MLB and significantly increases the application of risk treatment.

5.2 Ecological impacts of the Scenario I strategies

Consideration of tree species composition within the MLB (Figure 5) reveals that the EVEN strategy is best for wildlife values because it produces a landscape with the highest proportion of conifer species preferred by wildlife (fir, spruce, larch) and the lowest proportion of the less-favoured pine. The NPV strategy is worst for wildlife values, with a landbase that averages about 68% of the wildlife-preferred conifers generated by the EVEN strategy over the planning horizon. Additionally, the NPV strategy has a high proportion of the less-desirable pine in the MLB. The EVEN strategy produces the most favorable tree species composition for wildlife values, and is followed by the SUM strategy. The four strategies do not differ in the deciduous tree composition.

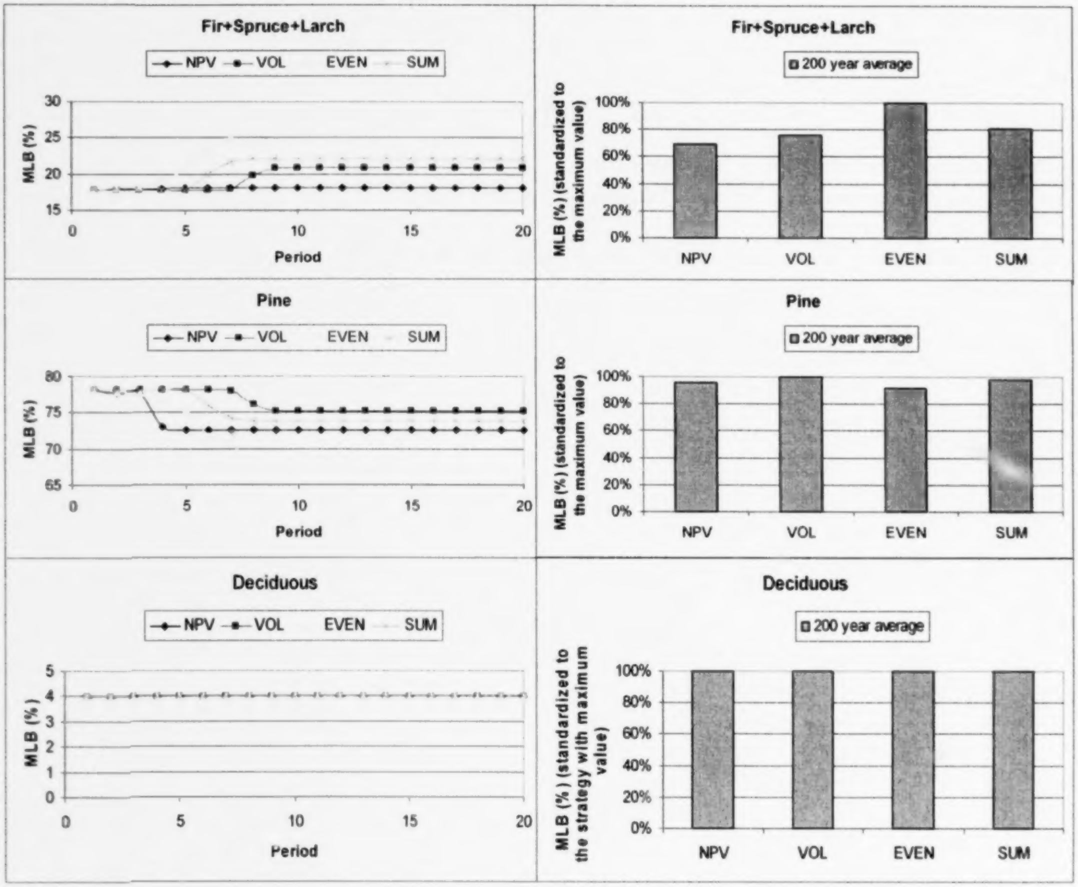

Figure 5. Scenario I tree species composition: percentage of the MLB over time (left), and 200-year average standardized to the strategy with the maximum value (right).

Consideration of the age class distribution of non-pine conifers preferred by wildlife (Figure 6) reveals that the VOL strategy has the highest proportion of forests of Age Class 3, followed by the SUM strategy, while the EVEN and SUM strategies resulted in similarly high proportions of Age Class 4. To the extent that mature forest cover is particularly limiting in a landscape with both extensive beetle kills and extensive logging disturbances, the SUM strategy may be considered to be best for habitat values as it will best support wildlife species that depend on mature forests (both Age Class 3 and Age Class 4). This holds true on average over the planning horizon and also in the second half of the planning horizon. Over the whole horizon, the NPV strategy has consistently had the lowest average coverage of mature forests. The EVEN strategy generates the landscape with the highest proportion of early forest classes (Age Class 1 and Age Class 2).

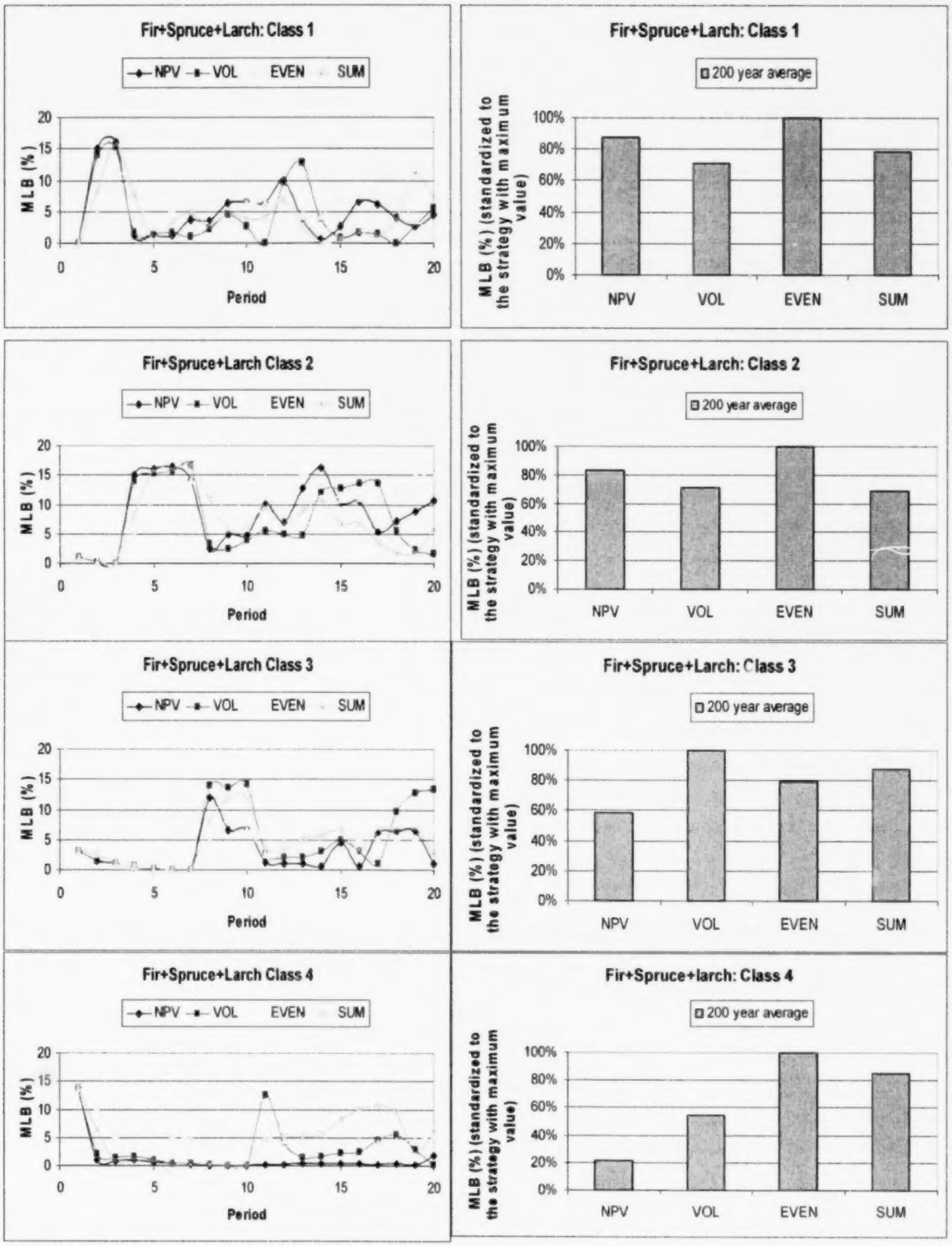

Figure 6. Scenario I age class distribution of wildlife-preferred conifers: percentage of the MLB over time (left), and 200-year average standardized to the strategy with the maximum value (right).

When the age class distribution of deciduous trees (Figure 7) are averaged over the planning horizon, the SUM strategy results in the highest proportions of mature forests (both Age Class 3 and Age Class 4). By period 6, however, mature deciduous trees in Age Class 4 were disappearing in all strategies. The NPV strategy has the lowest proportion of mature deciduous trees in the MLB among all strategies.

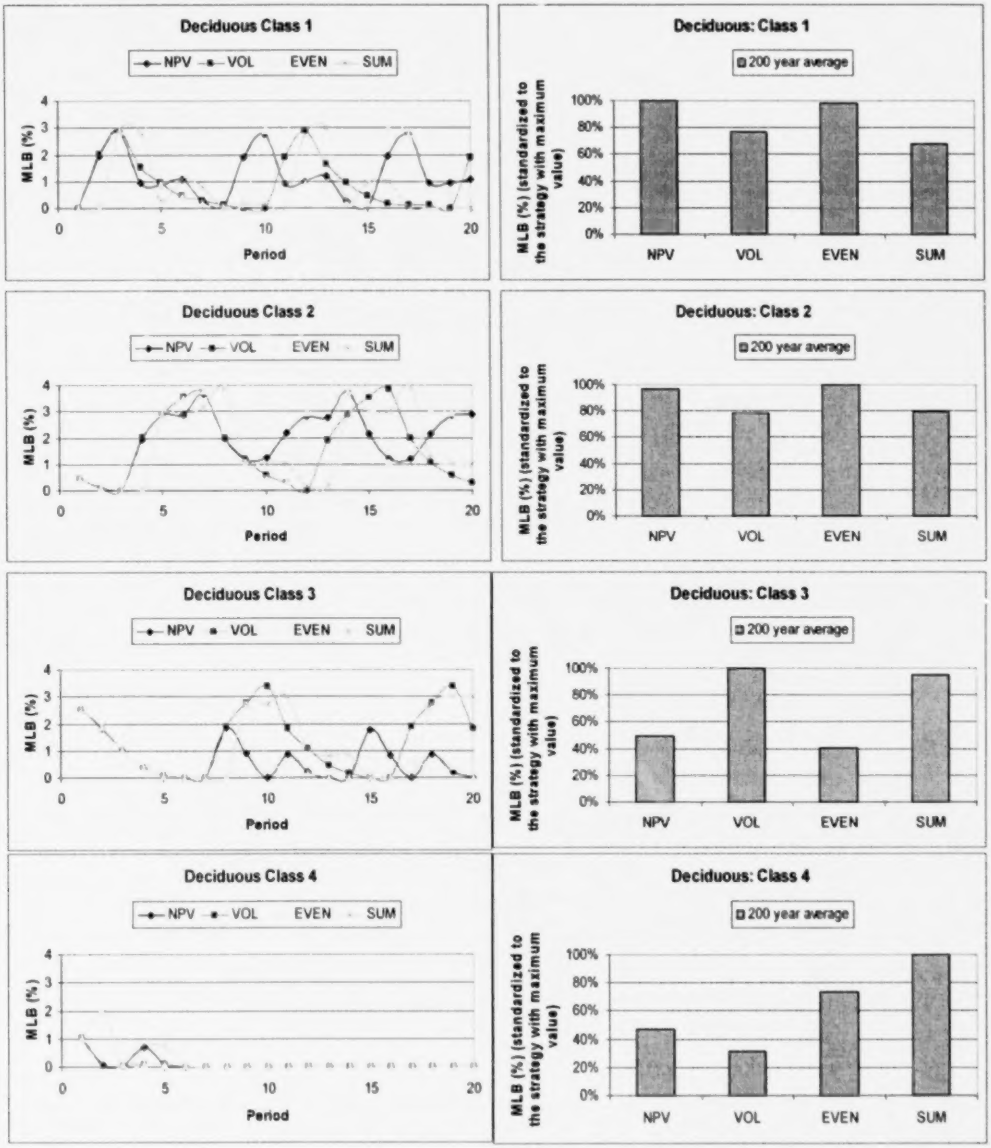

Figure 7. Scenario I age class distribution of deciduous trees: percentage of the MLB over time (left), and 200-year average standardized to the strategy with the maximum value (right).

When averaged over the 200-year planning horizon, the SUM period strategy has the lowest annual harvest area (Figure 8, right) and therefore the least amount of destroyed habitat and presumably the least landscape fragmentation. In addition, the SUM strategy does not exhibit significant peaks of annual harvest in any periods over the horizon (Figure 8, left). In contrast to the SUM strategy, the NPV strategy had the highest mean harvest area over the horizon. The VOL and EVEN strategies have approximately equal mean annual areas of harvest.

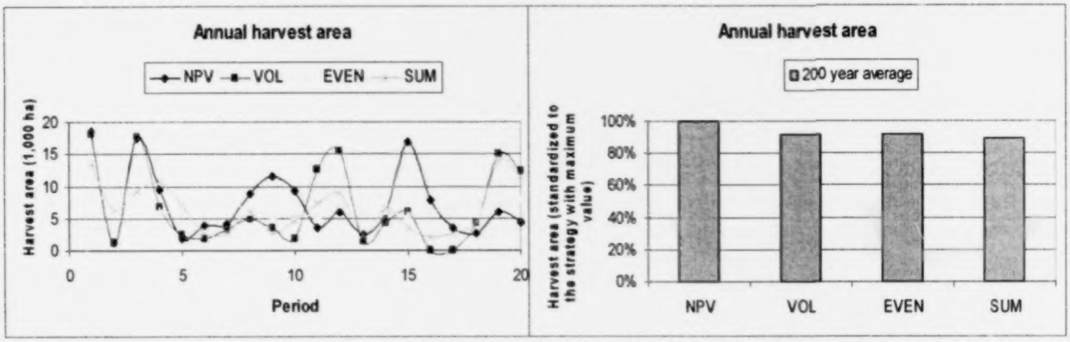

Figure 8. Scenario I annual harvest area: percentage of the MLB over time (left), and 200-year average standardized to the strategy with the maximum value (right).

5.3 Wildlife habitat impacts of the Scenario I strategies

All management strategies will likely result in adequate habitats for 23% of the wildlife species in the MLB that inhabit early seral stages, including 8.3% of the furbearers and 14.7% of the big game. However, to the extent that mature forest cover is particularly limiting in a landscape with both extensive beetle kills as well as extensive logging disturbances, strategies that result in the maximum coverage of Class 3 and Class 4 forests will be deemed to have a higher conservation value. In the MLB, 28% of all wildlife species have critical requirements for these mature forests, including 42% of the furbearers and 14% of the big game.

By almost all measures used in the analyses, the SUM strategy results in the highest wildlife-habitat values in the MLB. The SUM strategy has the highest proportion of wildlife-preferred conifer species, the best age class distribution for habitat-limited mature-forest dwelling wildlife, and the lowest mean-harvest area over the planning horizon.

By all measures used in the analyses, the NPV strategy resulted in the lowest wildlife-habitat values in the MLB. The NPV strategy had the lowest proportion of wildlife-preferred conifer species, the worst age class distribution for habitat-limited mature-forest dwelling wildlife, the fewest mature deciduous trees valued by many wildlife species, and the highest level of habitat destruction and fragmentation measured by mean harvest area over the planning horizon.

The VOL and EVEN strategies resulted in wildlife habitat values that were intermediate to those of the SUM and NPV strategies. The ranking of the VOL and EVEN strategies within the intermediate range changed depending on the index used to measure wildlife-habitat value.

5.4 Tree species composition and timber supply impacts of the Scenario II strategies

Scenario II addresses both forest resilience and economic diversification. To achieve these two goals, several authors suggested introducing the renewal strategies that promote a change of the current tree species composition (BC MoFR 2008). Following the workshop conclusions and the literature review, planting tree species adaptable to climate change was added as an option to planting the regional coniferous and deciduous tree species as part of the risk treatment. A recent study projected a significant shift of tree species in British Columbia as a result of changing climatic conditions (Hamann and Wang 2005). This study predicted an increasing occurrence of Douglas-fir and western larch in the British Columbia areas north to the current occurrence of these species. Under Scenario II, we consider planting western larch as an option within risk treatment.

The initial and target compositions of tree species are presented in Table 13.

Table 13. Initial and target tree species composition.

Tree Species	Douglas-fir	Spruce	Pine	Deciduous	Larch
	Composition (% MLB)				
Initial	4.9	12.9	78.2	4	0
Target	15	15	45	10	15

Each criterion function is optimized individually over the set of feasible strategies. The criteria values calculated at the optimal strategies are presented in Table 14. For example, the elements of the first column are criteria values when maximum deviation from the target species distribution is minimized (DIVERS strategy). As in Table 9, the ideal values are provided in boldface. These are the best possible values of each criterion. The underlined figures correspond to the worst criteria values. Figures in parentheses indicate the extent to which the ideal criteria values are reached by the strategy indicated in the column headline.

Table 14. Scenario II single-criterion strategies.

	Single-criterion strategies		
Criteria values	DIVERS	VOL	EVEN
TreeDev(x)[b] (%)	**1.94**[a]	29.13	<u>49.72</u>[a]
	(100.0%)	(43.1%)	(0.0%)
V(x) (mil. m^3)	<u>178.557</u>	**384.028**	305.394
	(46.5%)	(100.0%	(79.5%)
FlowD(x)[b] (mil. m^3)	25.722	<u>40.000</u>	**0**
	(35.7%)	(0.0%)	(100.0%)

[a] Best values are given in bold; worst values are underlined.

[b] Expressed as a deviation from the target species composition.

[c] Expressed as a deviation from the constant period volume.

As the criteria values calculated for the single-criterion strategies DIVERS, VOL and EVEN suggest, all criteria are in conflict. The conflict is especially marked between meeting the tree species composition target and timber supply benefits, but there is also a conflict between the cumulative harvest and even harvest flow over the horizon. The DIVERS strategy leads to the lowest cumulative harvest of 178.557 million m^3 (only 46.5% of the highest possible harvest). On the other hand, the high cumulative harvest volume goal is in strong conflict with the EVEN

strategy leading to the highest deviation of 40 million m^3 per period from stable harvest (4 million million m^3 of annual harvest).

None of the single-criterion strategies seems to be fully acceptable; a compromise strategy was constructed by solving (4). As for Scenario I, our first choice for the weighting scheme was to assign equal weights to each criterion of the weighted sum in (4). The resulting strategy implied large deviations of annual harvests between the consecutive periods. After experimenting with several weighting schemes, the weight of 0.85 was assigned to the harvest flow deviation criterion. The remaining 0.15 (obtained as the difference between the required sum of all weights of 1 and 0.85) was split between minimizing tree species diversity and maximizing cumulative volume as 0.05 to 0.10, respectively. Table 15 shows the criteria values calculated at the SUM compromise strategy obtained by solving (4) with weights 0.05, 0.1, and 0.85 assigned to *TreeDev*, *V*, and *FlowDev*, respectively.

Table 15. Scenario II compromise strategy.

	Compromise strategy
Criteria values	SUM
TreeDev(x)[b] (%)	1.96 (100.0%)
V(x) (mil. m^3)	326.000 (84.9%)
FlowD(x) (mil. m^3)	0.735 (98.2%)

The compromise SUM strategy looks promising in terms of achieving the satisfactory criteria values. Analyses of other outcomes may help in selecting a strategy. The outcomes selected for the analysis are distributions of the annual harvest volume and the annual volume by specific grades and species.

The distribution of the annual harvest volume for the four strategies is presented in Figure 9.

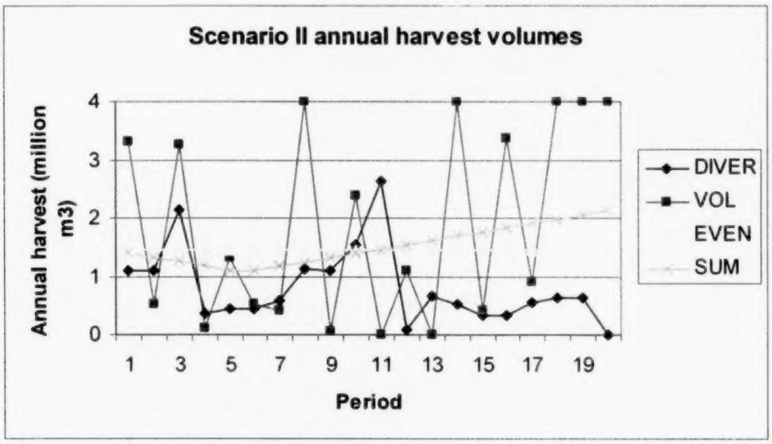

Figure 9. Scenario II annual harvest volumes.

The annual harvest patterns for the EVEN strategy are almost identical for Scenarios I and II. The annual harvest patterns for the VOL strategy are similar for Scenarios I and II over periods 1 to 4. From period 5 onward, the annual harvest patterns for the VOL strategy differ for the two

scenarios, possibly due to the different species that are introduced for planting within the risk treatment. The DIVERS strategy provides a constant harvest volume of about 1 million m^3 over the first two periods; the annual harvest doubles in period 3 and then drops to about 350 thousand m^3 in period 4. SUM is the only strategy other than the EVEN strategy that does not result in abrupt fluctuations of annual harvests over a long time. The compromise SUM strategy implies a slow decline of annual harvest until period 5 when a slow but steady recovery starts. In the light of its good performance in terms of meeting the target species composition, the compromise SUM strategy for Scenario II appears as a good candidate for application. However, it needs to be further examined. Additional insights into the potential benefits and/or drawbacks of strategies are provided by examining the harvest volume distribution by grades and species in Table 16.

Table 16. Scenario II harvest volume by grades and species.

		Harvest volume (% of cumulative)								
		Grades				Species				
Strategy	Cum.volume (mil. m^3)	1	2	4	6	Fir	Spruce	Pine	Decid.	Larch
DIVERS	162.677	8.2	78.9	11.2	1.6	13.5	11.3	46.3	14.5	14.5
VOL	376.725	12.1	77.0	9.9	1.0	6.3	18.3	31.3	17.9	26.3
EVEN	289.002	9.9	78.4	10.4	1.3	7.0	15.1	35.1	24.3	18.4
SUM	304.174	10.8	77.3	10.7	1.1	11.7	17.5	34.6	13.4	22.7

Under Scenario II, cumulative harvest volume over the horizon varies from 162.7 million m^3 for the DIVERS strategy to 376.7 million m^3 for the VOL strategy. The variations across strategies also occur in the grade 1 category. Not only is the SUM strategy competitive with the EVEN strategy in terms of cumulative volume, it also generates the largest quantity of the two highest grades which is important for economic benefits not considered explicitly in this scenario.

For each renewal treatment, Table 17 provides distributions of renewal treatments—default, productivity and risk—in terms of the portions of the total harvest area over the horizon.

Table 17. Scenario II harvest area by renewal treatments.

		Renewal treatments (% of harvest area)		
Strategy	Total harvest area (mil. ha)	Default	Risk	Productivity
DIVERS	0.833	51.9	48.1	0.0
VOL	1.319	67.7	32.3	0.0
EVEN	1.188	64.1	35.9	0.0
SUM	1.259	68.2	31.8	0.0

It may come as a surprise that no strategy under Scenario II employs the productivity treatment. The productivity treatment involves intensive management of stands planted by pine. This treatment does not help by increasing the total merchantable volume significantly, but it shifts the volume distribution toward higher grades. This further helps create higher financial benefits. However, as financial benefits are not included among the model criteria, none of the strategies employs the productivity treatment.

The distributions of various tree species planted for the risk treatment is presented in Figure 10.

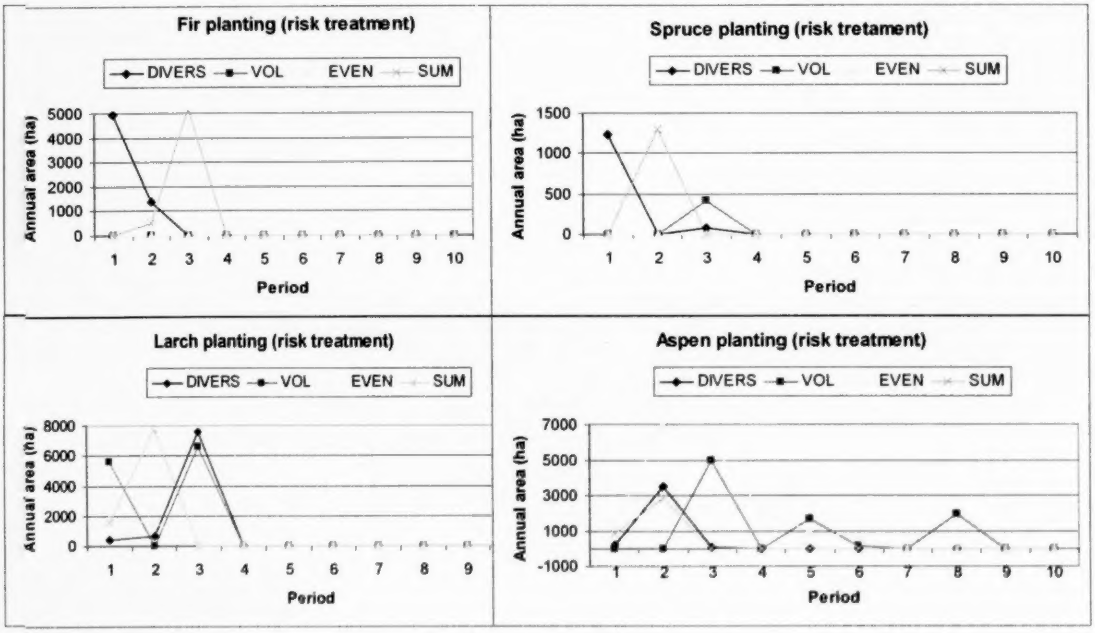

Figure 10. Scenario II risk treatment (planting by tree species).

Scenario II allows for planting combinations of several tree species within the risk treatment. While both the DIVERS and SUM strategies consider planting fir and spruce, large areas are planted by larch for all strategies except the EVEN strategy. Instead, this strategy relies on planting aspen in the risk treatment. Not only does aspen help meet the species diversity criterion, its fast growth contributes to a steady harvest flow over time.

5.5 Ecological impacts of the Scenario II strategies

The patterns of the wildlife-preferred conifers (fir, white spruce and western larch) were quite similar for all, except EVEN, strategies. The proportion of the wildlife-preferred conifers in the MLB increases rapidly in the first four periods of the planning horizon and stabilizes afterwards at the levels between 38% for the VOL and 44% for the DIVERS and SUM strategies. The lowest portion (23% of the MLB of the wildlife-preferred conifers) is achieved for the EVEN strategy. On the other hand, all strategies resulted in very similar patterns of the proportion of pine trees in the MLB that decreases rapidly in the first four periods of the planning horizon and stabilizes afterwards at the levels between 44% and 46%. The highest deciduous tree coverage in MLB is for the EVEN strategy followed by the VOL strategy.

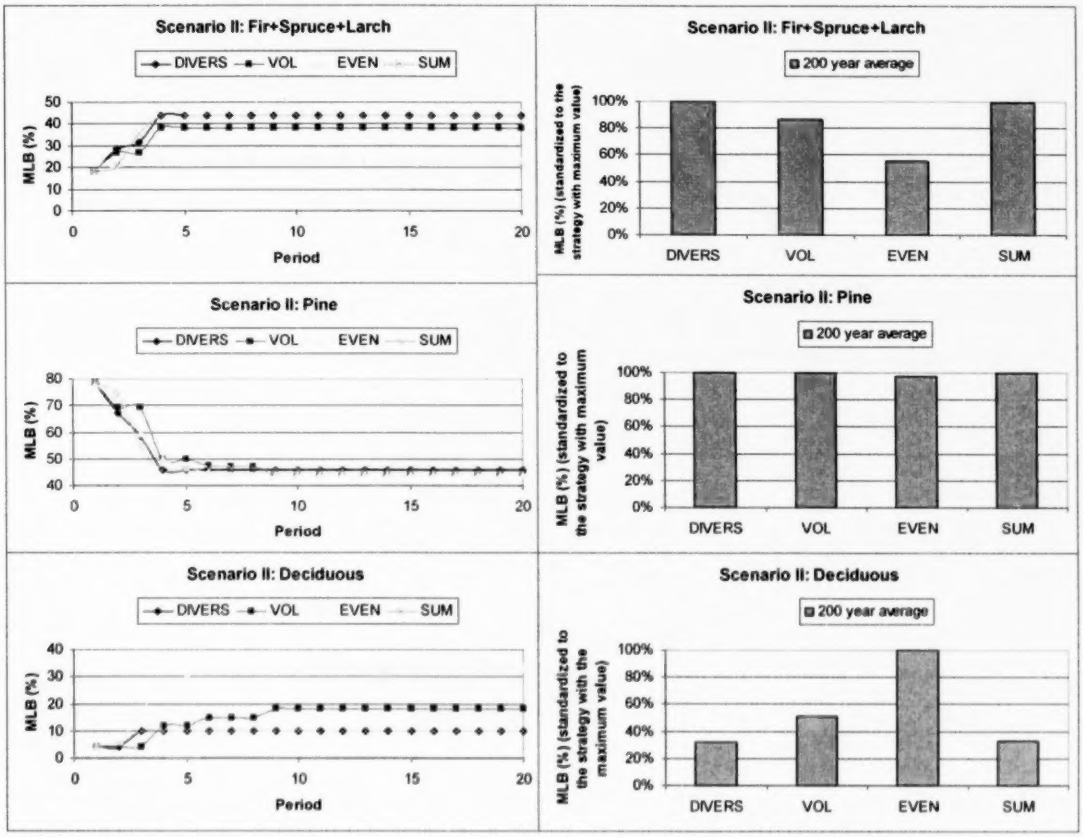

Figure 11. Scenario II tree species composition: percentage (%) of the MLB over time (left), and 200-year average standardized to the strategy with the maximum value (right).

The strategies follow relatively similar patterns of early forest age over time (Age Class 1 and Age Class 2 in Figure 12). The highest portion of early seral stage (both Age Class 1 and Age Class 2) occur for the SUM strategy followed by the EVEN strategy, but moderate differences in the mature age classes (Class 3 and Class 4) are apparent when these are averaged over the planning horizon. The DIVERS strategy results in the large proportions of both Age Class 3 and Age Class 4. The SUM strategy performs well in terms of the Age Class 3 and it is also second of all the strategies in terms of Age Class 4. The EVEN strategy has the lowest values of Age Class 3 and Age Class 4 combined.

When the age class distribution of deciduous trees (Figure 13) are averaged over the planning horizon, the SUM strategy results in the lowest proportions of mature forests (both Age Class 3 and Age Class 4). While almost non-existent in the first half of the horizon, mature deciduous trees of Age Class 4 start increasing in the second half of the horizon for the DIVERS and VOL strategies.

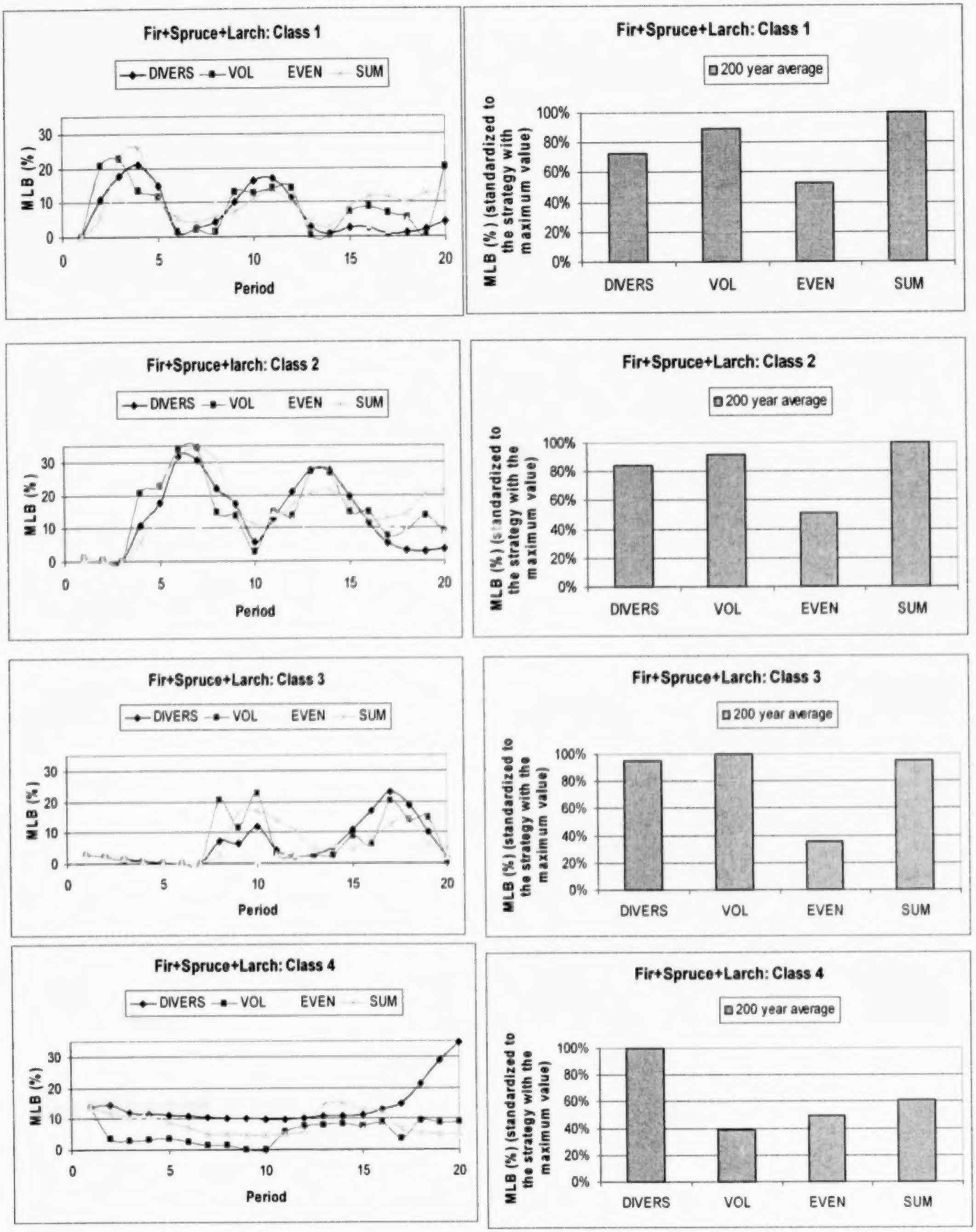

Figure 12. Scenario II age class distribution of wildlife-preferred conifers: percentage of the MLB over time (left), and 200-year average standardized to the strategy with the maximum value (right).

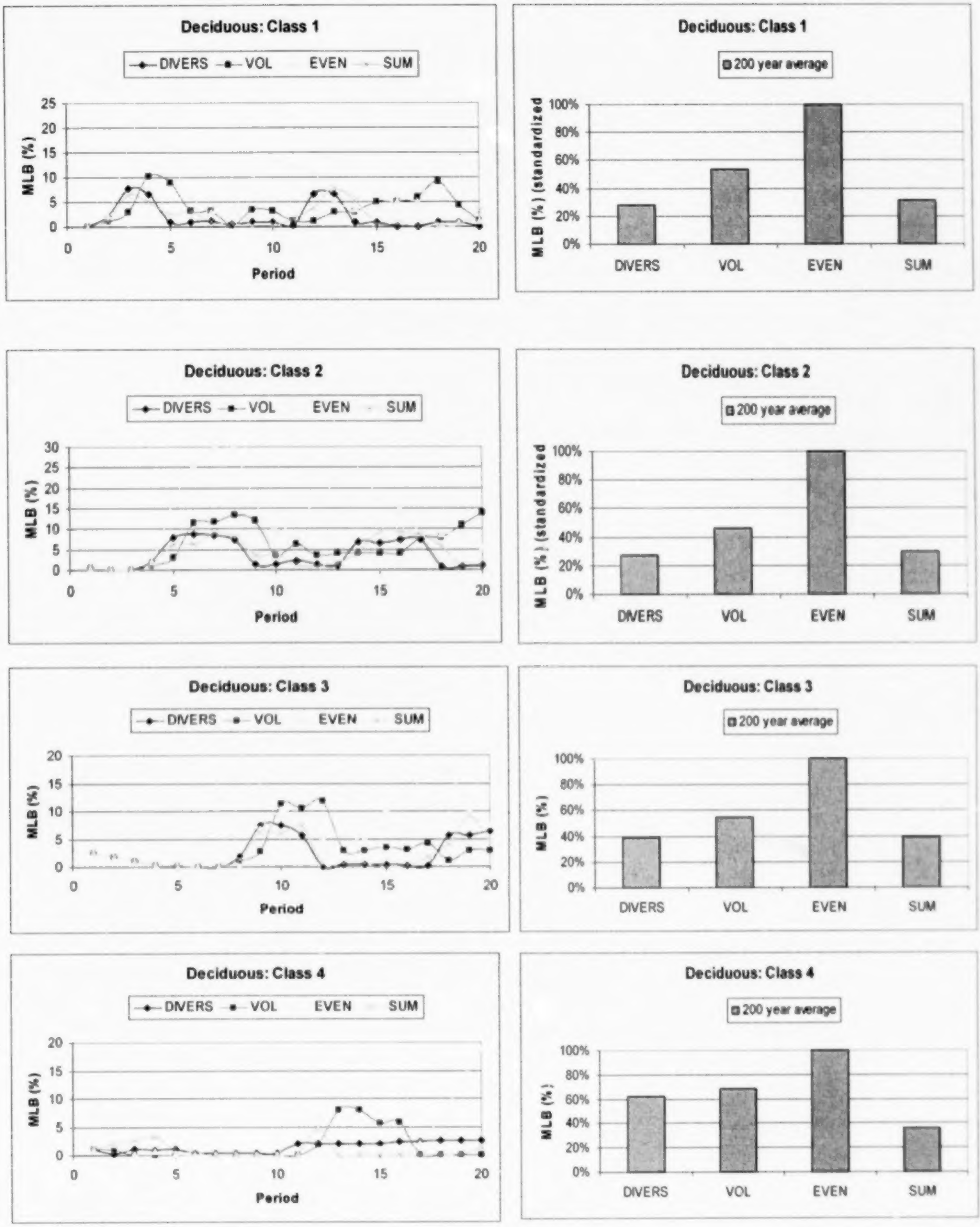

Figure 13. Scenario II age class distribution of deciduous trees: percentage of the MLB over time (left), and 200-year average standardized to the strategy with the maximum value (right).

The annual harvested area is lowest for the DIVERS strategy (Figure 14). All other management strategies resulted in similarly high areas of harvest that were at least 33% higher than that of the DIVERS strategy. The VOL strategy has the highest average rate of harvest over the 200-year period.

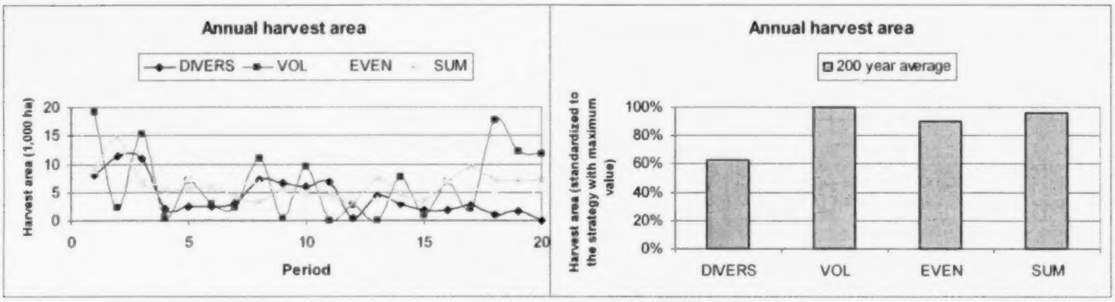

Figure 14. Scenario II annual harvest area: percentage (%) of the MLB over time (left), and 200-year average standardized to the strategy with the maximum value (right).

5.6 Wildlife habitat impacts of the Scenario II strategies

The different renewal strategies result in different wildlife habitat values in the MLB, especially in the coverage of deciduous trees, which have high wildlife habitat value. All strategies have almost identical coverage of pine both in terms of the average and distribution over time. Patterns of the wildlife-preferred conifers (fir, white spruce and western larch) were quite similar for all except EVEN strategies. The greatest difference between strategies was observed when annual differences in the age class distribution of wildlife-preferred conifers were averaged over the horizon; these cumulative differences approach 40% or more between strategies.

There is no strategy that is the best by all measures used in the analyses. The DIVERS strategy results in the highest proportion of wildlife-preferred conifer species and the lowest habitat destruction and fragmentation as indexed by mean harvest area averaged over 200 years. The SUM strategy has the same highest proportion of wildlife preferred conifer species as the DIVERS strategy, while the EVEN strategy has the highest proportion of deciduous cover valued by wildlife.

As with the best strategy, there is no strategy that has the lowest wildlife habitat values by all measures used in the analyses. Both the DIVERSE and SUM strategies have the lowest coverage of deciduous trees; the EVEN strategy has among the lowest proportion of wildlife preferred conifer species, and the fewest areas of mature forests, while the VOL strategy has the highest average annual harvest area.

In order to provide better ranking of the strategies in terms of their wildlife-habitat impact, additional indexes are needed. However, this research is beyond the scope of this project.

6 Discussion

The two key scenarios identified for the Quesnel area represent different desired community futures. The *strong forest sector* (Scenario I) may be considered a status quo scenario since it relies on standard regeneration treatments and follows pretty closely the current tree species composition. Under this scenario, three single criterion renewal strategies are generated followed by a compromise strategy that is aimed to meet a weighted sum of the three single criteria. Unlike timber supply models used for Annual Allowable Cut calculation that consider only the timber supply criteria, we included a financial criterion into the modeling under Scenario I.

Scenario II—*forest resilience/economic diversification*—aims to reduce both ecological and market risks in the future. This scenario's intention is to explore novel renewal strategies, and their multiple impacts and tradeoffs. The scenario focuses on diversifying the regional economic base and improving the structural diversity of forests in order to reduce both market-related and ecological risks.

The management strategies generated under the two scenarios differ significantly in the criteria values, in the outcomes values and in the distribution of renewal treatment. The scenarios are first compared in terms of the criteria values (Table 18).

Table 18. Criteria values for the Scenario I and Scenario II strategies.

	Strategy			
Criteria values	Single-criterion			Compromise
	Scenario I			
	NPV	VOL	EVEN	SUM
N(x) (million $)	1186.194	1129.318	796.739	1033.231
V(x) (million m^3)	280.187	328.102	293.735	322.640
FlowD(x) (million m^3)	38.056	37.495	0	8.998
	Scenario II			
	DIVERS	VOL	EVEN	SUM
N(x) (million $)	348.270	942.820	502.490	402.370
V(x) (million m^3)	178.557	384.028	305.394	326.000
FlowD(x) (million m^3)	25.722	40	0	0.735

Economic benefits, expressed in terms of cumulative discounted net return over the planning horizon, are significantly higher for Scenario I than the benefits for Scenario II across all corresponding strategies. At the same time, total harvest volumes across the same strategies are slightly higher for Scenario II than volumes for Scenario I. In terms of the harvest flow over time, Scenario II scores better than Scenario I, in particular, for the compromise strategy. Explanations for these somewhat controversial results could be found in analyzing distributions of harvest by grades and species (Table 19).

For Scenario II, the grade 1 portion of harvest volume increases significantly across all strategies compared to Scenario I (Table 19). This increase cannot compensate for the decreasing grade 2 portion of harvest volume for Scenario II relative to Scenario I. Another reason for reduced NPV under Scenario II is a large contribution to harvest of low-priced deciduous wood (Table 19). Finally, both the diversity and even flow criteria cause a reduction in the early period harvest volume, which further implies a significant drop in the discounted net returns.

Table 19. Harvest volume by grades and species for Scenario I and Scenario II.

		Harvest volume (% of cumulative)								
		Grades				Species				
Strategy	Cum.volume (mil. m^3)	1	2	4	6	Fir	Spruce	Pine	Deciduous	Larch
		Scenario I								
NPV	280.187	5.3	85.2	8.5	1.2	6.8	20.6	66.1	6.4	0
VOL	328.102	3.8	82.7	10.8	2.5	6.6	21.6	65.5	6.2	0
EVEN	293.735	4.4	84.2	9.8	1.6	6.6	26.4	61.1	5.9	0
SUM	322.640	6.2	82.5	9.9	1.3	6.8	25.2	61.9	6.1	0
		Scenario II								
DIVERS	178.557	8.2	78.9	11.2	1.6	13.5	11.3	46.3	14.5	14.5
VOL	384.028	12.1	77.0	9.9	1.0	6.3	18.3	31.3	17.9	26.3
EVEN	305.394	9.9	78.4	10.4	1.3	7.0	15.1	35.1	24.3	18.4
SUM	326.000	10.8	77.3	10.7	1.1	11.7	17.5	34.6	13.4	22.7

Finally, scenarios are compared in terms of the renewal treatments employed by the strategies presented in Table 20. It comes as no surprise that all strategies for Scenario II have a high allocation of post-harvest to risk treatment. What was not expected is no use of productivity treatment under Scenario II. After all, it is the implication of no economic criterion included into this scenario.

Table 20. Renewal treatments for Scenario I and Scenario II.

	Renewal treatment (% of harvest area)			
Strategy	Total harvest area (mil. ha)	Default	Risk	Productivity
	Scenario I			
NPV	1.451	97.6	0.1	2.3
VOL	1.333	98.6	1.4	0.0
EVEN	1.329	94.7	5.1	0.2
SUM	1.296	97.9	2.1	0.0
	Scenario II			
DIVERS	0.833	51.9	48.1	0
VOL	1.319	67.7	32.3	0
EVEN	1.188	64.1	35.9	0
SUM	1.259	68.2	31.8	0

None of the strategies generated for the two scenarios is superior in terms of all criteria and additional outcomes considered. The novel renewal treatments considered for Scenario II and explicit requirements for meeting a certain target of tree species composition seem promising. One possibility is to design new scenarios that include both the economic benefits and wildlife habitat requirements along with the criteria defined for Scenario II.

The integrated framework developed for this study is general and allows for other community and forest management and concerns to be incorporated. The framework demonstrates how the stakeholders' goals regarding their community's future are formulated and how the conflicts between multiple criteria could be addressed.

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Appendices

Appendix I

Table A1. List of indicators with the corresponding preferences scores over the mid- and long-term horizon.

Indicator	Preference Scores	
	Mid term	Long term
Increase total employment	57.7	68.1
Diversify employment across sectors [a]	76.6	85.2
Increase annual income per capita	0.0	61.2
Diversify community dependence across sectors [a]	69.4	85.4
Maintain existing area of protected forests for recreation, cultural and spiritual values	71.8	78.8
Increase area of protected forests for recreation, cultural and spiritual values	59.8	63.6
Increase annual harvest of non-timber forest products	61.0	65.8
Maintain a stable flow of timber harvested over time	57.8	79.9
Maintain existing area of old-growth forests	57.8	67.1
Restore forests affected by MPB by planting:		
Tree species other than pine	78.0	80.8
Native [b] tree species that could adapt to future climate	83.0	85.9
Non-native[c] tree species that could adapt to future climate	0.0	45.0
Native [b] tree species more resistant to pest attacks	57.1	61.1

[a] agriculture, forestry, tourism and recreation, mining, etc.

[b] native to the region.

[c] non-native to the region.

From all indicators, the highest score is given to *native species that could adapt to climate change* (mid term=83 and long term=85.9). The second most important indicator related to forest management is *planting species other then pine* (mid term=78 and long term=80.8). Another high-scored indicator is *increase annual non-timber harvest over time* (mid term=61 and long term=65.8).

From the socio-economic criteria, the highest importance was given to the diversification of employment across sectors (mid term=76.56 and long term=85.2) and diversification of community dependence across sectors.

High scores were also given the indicators *maintain existing area of old-growth forests* (mid term=57.8 and long term=67, 11) and *increase area of protected forests for recreation, cultural and spiritual values* especially in the long term when the value reached 63.5 (mid term=60).

Participants identified the key uncertainties facing the forest sector and community: wood-product markets and concerns with regard to climate change. Concerns about climate change are reflected in the scoring when the absolute highest score was given to *planting native tree species that could adapt to future climate*.

Appendix II

This appendix contains the assumptions used in the modeling procedures for the Quesnel analysis. The land base assumptions are based on two key documents, the consulting reports developed for the Quesnel TSA (Buell et al. 2006; FESL 2008). Data used in the modeling procedures for the Quesnel analyses were built on results provided by Forest Ecosystems Solutions Ltd. (FESL 2008).

Table A2. Distribution among tree species and site index classes within the MLB.

	Percentage (%) of the MLB			
	Site index classes			
Species	Good	Medium	Poor	Total
F	1.69	2.61	0.61	4.91
S	1.48	4.39	7.02	12.89
PL	5.38	26.33	29.92	61.63
PFT	0	2.57	14.01	16.58
Dec	0.13	3.85	0.01	3.99
Total	8.68	39.75	51.57	100

Table A3. Distribution among tree species and age classes within the MLB.

	Percentage (%) of the MLB				
	Age classes				
Species	1[a]	2[b]	3[c]	4[d]	Total
F	0	0.5	1.59	2.8	4.89
S	0	0.56	1.4	10.94	12.9
PL	0.03	11.99	15.46	34.15	61.63
PFT	0	1.23	10.44	4.9	16.57
Dec	0	0.44	2.5	1.05	3.99
Total	0.03	14.72	31.39	53.84	99.98

[a] Class 1: less than 20 yrs.

[b] Class 2: 21–60 yrs.

[c] Class 3: 61–90 yrs.

[d] Class 4: 90+ yrs.

Table A4. Distribution among tree species and BEC zones within the MLB.

	Percentage (%) of the MLB							
	Biogeoclimatic (BEC) zone							
Species	AT	SBPS	SBS	MS	ESSF	ICH	IDF	Total
F	0	0.23	4.17	0	0.06	0.19	0.25	4.9
S	0.04	3.55	3.18	1.85	3.85	0.41	0.02	12.9
PL	0	35.35	13.25	11.98	0.4	0.06	0.59	61.63
PFT	0	7.92	1.85	6.78	0.03	0	0	16.58
Dec	0	0.32	3.6	0	0.01	0	0.06	3.99
Total	0.04	47.37	26.05	20.61	4.35	0.66	0.92	100

Table A5. Percent of wildlife species using different types of forest habitats and forest attributes.

	Seral stage							
	Early	Middle	Late	Multiple	Shrub User	Downed Wood User	Deciduous Habitat	Edge/open Habitat
All Species	22.7	9.2	28.1	45.9	17.3	13.5	22.7	31.9
Herptiles	0.0	0.0	0.0	100.0	0.0	0.0	0.0	57.1
Mammals	16.7	0.0	33.3	50.0	10.4	41.7	20.8	33.3
Birds	26.2	13.1	27.7	41.5	20.8	3.8	24.6	30.0
Furbearers	8.3	0.0	41.7	0.5	0.0	75.0	8.3	41.7
Big Game	14.3	0.0	14.3	71.4	42.9	14.3	14.3	57.1